Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 131 **2026**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2026.131.6

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Kubielas-Walasek, J., Świrska-Perkowska, J., Pawlik, K. Dependence between the values of pavement friction coefficients determined by the stationary and continuous methods. *Scientific Journal of Silesian University of Technology. Series Transport*. 2026, **131**, 103-119. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2026.131.6

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DEPENDENCE BETWEEN THE VALUES OF PAVEMENT FRICTION COEFFICIENTS DETERMINED BY THE STATIONARY AND CONTINUOUS METHODS

Summary. The paper presents the results of pavement friction coefficient measurements carried out using the ViaFriction device (μ_{VF}) and the British Pendulum Tester (PTV), along with Mean Profile Depth (MPD) tests on asphalt pavements. Six road sections, each approximately 1 km long, were selected for the study, all paved with asphalt mixtures: four sections with SMA11, one with SMA8, and one with AC11. Correlations between datasets obtained from each device were then analyzed. It was found that friction coefficients μ_{VF} and PTV exhibited strong correlation when only SMA11 pavements were considered, and moderate correlation when all pavement types were included. The correlation between μ_{VF} and the MPD parameter was accordingly moderate or weak. Furthermore, multiple regression analysis was employed to determine the relationship between the friction coefficient μ_{VF} and the PTV and MPD values. In each case, an improvement in the fit of such a model to the measurement data was observed compared with the model describing a linear relationship between the coefficients μ_{VF} and PTV.

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Keywords: road pavement, friction coefficient, British Pendulum Tester, ViaFriction, MPD, correlation

1. INTRODUCTION

One of the key parameters determining road safety is skid resistance [1,2]. This has been confirmed by numerous experimental studies, which indicate that approximately 30% of all accidents are related to deterioration of pavement condition and its skid resistance properties [3,4]. In road engineering, skid resistance is most commonly defined as the force generated between a tire and the pavement when a locked (non-rotating) wheel slides along the road surface [5]. This force is associated with the coefficient of dynamic friction [6], which depends, among other factors, on the pavement material, its condition and contamination, as well as the construction and material of a tire [6,7]. However, in vehicle dynamics, a key parameter is the peak value of the friction coefficient, which occurs at a slip ratio of a tire equal to or below 0.2 that is, under partial wheel lock. In such conditions, the force generated at the tire-pavement interface results from both static and dynamic friction. The peak friction coefficient exceeds the value observed under full wheel lock (slip ratio of 1.0) by more than 1.2 times [6].

So far, two distinct friction mechanisms have been identified, arising respectively from adhesion and hysteresis phenomena. The first is related to weak molecular interactions between the substrate and the rubber and plays a significant role at low vehicle speeds [8]. The adhesion phenomenon depends on microtexture of the pavement, that is, the shape of aggregate grains used for its construction. The hysteresis component results from internal friction within the rubber: as the rubber moves over rough surfaces, it is subjected to oscillatory forces that cause cyclic deformations of the rubber and energy dissipation through internal damping [8,9]. Hysteresis friction is a dominant mechanism at high vehicle speeds, and its magnitude mainly depends on pavement macrotexture. For example, local variations in road roughness can contribute to changes in the predicted friction force by more than 50% [8].

It should be noted that the concept of tire adhesion to the road surface is closely related to the coefficient of friction of the surface. Accurate determination of adhesion is of crucial importance for road traffic safety, particularly for the operation of active safety systems such as ABS, ESP, and electronic brake-force distribution systems. In practice, the problem is complex because the adhesion depends on numerous factors, including road pavement type, tire condition, wheel slip, vertical load, and weather conditions [10]. The paper [10] analyses several well-known mathematical models describing the relationship between wheel slip and adhesion force. It is noted that different models accurately reproduce only selected operating ranges of the wheel, for example during acceleration or braking, whereas not all models correctly represent the entire range of motion from free rolling to wheel lock-up.

Due to immense importance of skid resistance of road pavements, continuous efforts have been made for many years to improve both laboratory and field methods for measuring the friction coefficient [3], as well as to identify relationships between results obtained using these methods. Existing measurement techniques can be broadly divided into two main groups. The first group involves indirect tests based on measurements of characteristics describing the microtexture and macrotexture of the pavement surface and predicting the pavement friction coefficient using appropriate models. This approach is addressed, for example, in studies [11-13]. The second group consists of direct tests, during which the friction coefficient of the pavement (field tests) or samples (laboratory tests) is measured directly [3]. Friction measurement devices can be categorized as devices for longitudinal friction measurement

(LFC), devices for measuring lateral force coefficient (SFC), and stationary devices such as the British Pendulum Tester (BPT) [3,5]. The research method employing the BPT, used to measure the dynamic friction coefficient, was developed in the 1960s [14] and remains one of the most commonly applied measurement methods in this field [3]. The BPT is a pendulum-style tester with a standard rubber slider set at an angle to ensure minimal contact with the surface of the tested pavement. Many researchers consider that results obtained using the BPT are related solely to microtexture of the pavement [15]; however, detailed analysis of the BPT's operation also confirms the existence of correlation between BPN results and pavement macrotexture [16].

As mentioned earlier, the efforts of many researchers have been focused on finding relationships between skid resistance measurement results obtained using different testing devices. For example, the study [15] presented the results of skid resistance tests carried out on ten selected road sections differing in asphalt mixture used in the wearing course. Friction coefficient measurements were conducted using the mobile TWO device, which consists of a pair of wheels (a measuring wheel and a reference wheel) connected by a chain drive. The measuring wheel is partially locked (slip ratio of 17.8%) and loaded with a force of 60 kg. Additionally, for the analyzed road sections, dynamic friction coefficient measurements were performed using the British Pendulum Tester (BPT) and Mean Texture Depth (MTD) was measured using the volumetric method (sand patch method). The friction coefficient obtained using the TWO device showed good correlation with values obtained from the BPT (determination coefficient R^2 greater than 0.8) as well as with MPD values (R^2 greater than 0.7).

In the study [3], skid resistance was examined on three test tracks with SMA11S asphalt pavements constructed using three different mineral aggregates (diabase, rhyolite, and basalt). Measurements were carried out for over four years, with a frequency of three times per year, using five different devices: the BPT test, Mean Texture Depth (MTD) test (optical profilometer), Outflow Meter (OFM) test, Wehner/Schulze (W/S) test, and longitudinal friction coefficient test (ViaFriction device). The ViaFriction device is a single-wheel friction measurement instrument with variable slip ratio ranging from 1% to 75% (standard slip ratio is set at 18%), performing continuous measurements. Low correlation was found between friction coefficient values obtained using the ViaFriction device and the BPT. The ViaFriction test results also showed no correlation with the Mean Texture Depth (MTD) index values. Additionally, it was confirmed that the type of aggregate significantly affects skid resistance of the asphalt pavement.

The authors of the study [17] described various devices used for measuring skid resistance properties of pavements and analyzed correlation between friction results obtained from stationary devices such as the California Skid Tester (CST) with slip ratio $s = 1$ and test speed $v = 80$ km/h, the British Pendulum Tester (BPT) with $s = 1$ and $v = 10$km/h, and the Dynamic Friction Tester (DFT) with $s = 1$ and v ranging from 0 to 90 km/h, as well as continuous measurement devices: the Locked-Wheel Skid Trailer with $s = 1$ i $v = 64$ km/h, the Mu-Meter with $s = 0.13$ i $v = 20 \div 80$ km/h, and the GripTester with $s = 0.145$ i $v = 30 \div 90$km/h. Good correlation (determination coefficient R^2>0.8) was found between the measurement results obtained with the BPT and those from the CST, DFT, and GripTester.

The aim of the study [18] is to attempt to develop a model linking friction coefficient with parameters describing the pavement texture. Roads with pavements made of mineral-asphalt mixtures differing in aggregate grading were selected for the study, including two highly porous mixtures, two mixtures with dense aggregate gradation, and one mixture of mastic asphalt. The texture of pavement samples was tested using a linear laser scanner. Field measurements were conducted using the BPT, DFT, and micro-GripTester. Statistical analysis of the experimental results using linear regression showed no universal relationship between texture and friction. Although statistically significant, this relationship takes a different form for each type of pavement. Furthermore, the authors concluded that MPD is the most important pavement texture parameter for describing various friction measurements.

The paper presents the results of friction coefficient measurements on six different roads with pavements made of mineral-asphalt mixtures having maximum aggregate sizes of 11 or 8 mm. All tested road sections were approximately 1 km long. The friction coefficient was measured continuously using the ViaFriction (VF) device at slip ratio $s \cong 0.18$ and test speed $v = 60$ km/h, as well as by a stationary method using the British Pendulum Tester (BPT) with measurement points spaced every 100 m. Simultaneously, the Mean Profile Depth (MPD) of pavements was measured using a laser profilometer attached to the VF device in front of the test wheel. The study investigated the correlation between friction coefficient values obtained by continuous and stationary methods. Additionally, assuming that BPT readings correspond to pavement microtexture and MPD values represent the macrotexture [15], a linear regression method was used to determine the relationship between ViaFriction readings and the PTV values (BPT readings) and MPD of the tested road sections. The friction coefficient predicted in this way showed very good agreement with the friction coefficient determined using ViaFriction.

2. SKID RESISTANCE PROPERTIES OF ROAD PAVEMENTS

2.1. Coefficient of Friction and Road Surface Texture

Frictional properties between a tire and road pavement are a key factor that must be taken into account in the design of safe transport infrastructure. Friction generated at the tire-road interface arises from two primary mechanisms: adhesion and hysteresis of rubber. Adhesion results from molecular interactions between vehicle tire rubber and the surface of the pavement. Microtexture plays a significant role due to contact with coarse aggregate particles in the mixture. Adhesion is primarily responsible for friction on dry and smooth surfaces. Hysteresis, on the other hand, stems from energy losses caused by deformation of a tire. It dominates on wet and rough pavements and is mainly influenced by the macrotexture of the surface [19].

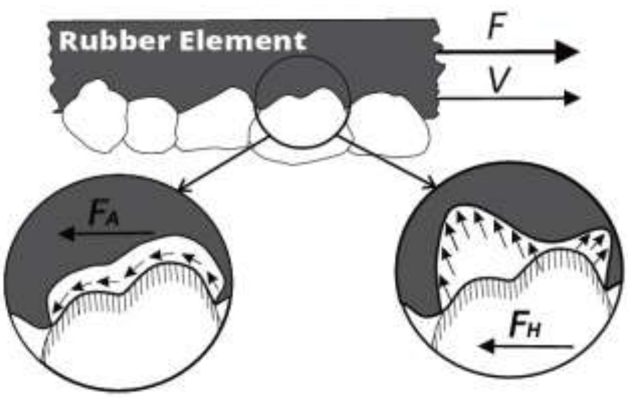

Fig. 1. Key mechanisms of pavement-tire friction [20]

Skid resistance of pavements can be described using the friction coefficient (μ), a dimensionless parameter defined as the ratio of frictional force to regular force acting at a tire-pavement contact area. It is a fundamental parameter for road safety, influencing, among other things, braking distance and vehicle behavior on curves or during maneuvers [21]:

$$\mu = F/F_w, \tag{1}$$

where: μ – friction coefficient [–], F – friction force [N], F_w – vertical load [N].

The frictional performance of road pavements is influenced by various factors, which may be categorized into four main groups: pavement characteristics, vehicle operating parameters, tire properties, and environmental conditions. Pavement characteristics are primarily described by surface texture. The World Road Association (PIARC) defines texture in terms of wavelength as deviation of surface ordinates from a theoretically flat surface, and distinguishes three primary scales of texture: microtexture, macrotexture, and megatexture. Microtexture corresponds to wavelengths in the range of 0 to 0.5 mm. It is directly associated with mineralogical composition of aggregate and is dependent on the resistance of coarse aggregate to polishing. Microtexture is critical in enabling the disruption of a water film present at the tire-pavement interface.

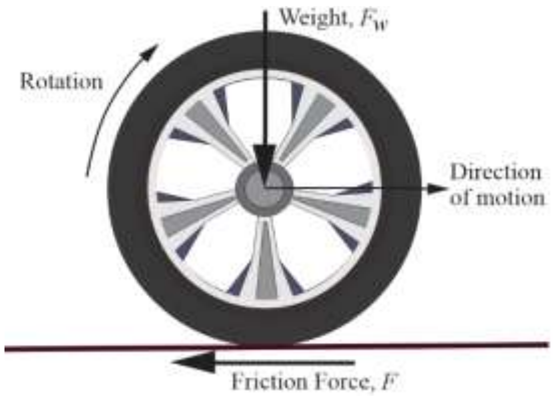

Fig. 2. Simplified diagram of forces acting on a rotating wheel [20]

Macrotexture is determined by the type of asphalt mixture and, in case of concrete pavements, by a texturing technique applied. The wavelength of macrotexture falls within the range of 0.5 mm to 50 mm. It is responsible for facilitating water drainage from the pavement surface, thereby reducing the likelihood of aquaplaning [22].

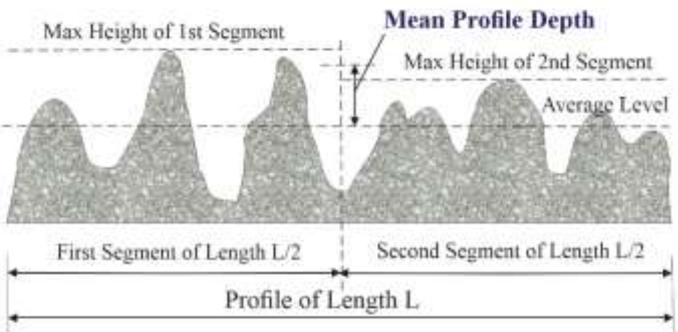

Fig. 3. Average value of the profile depth of the tested section [23,24]

The assessment of pavement skid resistance is not solely based on measurement of the friction coefficient. It requires knowledge of both macrotexture and microtexture. Macrotexture can be determined using the volumetric method as Mean Texture Depth (MTD), or by a profilometric approach as Mean Profile Depth (MPD), calculated as the average value across individual surface segments [23]. The microtexture of the road surface may be assessed indirectly by specifying the corresponding BPN value, since the measurement results obtained using the BPT depend primarily on the microtexture of the tested surface [15,18].

2.2. Devices for Testing the Coefficient of Friction

To evaluate skid resistance under real-world conditions, four primary groups of measurement devices are distinguished [25]:

- Side-force testers, which measure frictional forces acting perpendicular to the plane of the test wheel, inclined at an angle of 7.5° to 20° relative to the movement direction (e.g., SCRIM, Mu-Meter, Stradograf);
- Fixed slip devices, which measure frictional forces acting on a test wheel aligned with the movement direction at constant slip ratio (e.g., GripTester, TWO);
- Variable slip devices, which measure frictional forces acting on a test wheel aligned with the movement direction with variable slip ratio (e.g., ROAR, Petra, ViaFriction);
- Locked-wheel testers, which measure frictional forces acting on a fully locked test wheel aligned with the movement direction (e.g., Adhera, SRT-3).

Under European practice, the most commonly used devices belong to the “side-force” and “fixed slip” categories. These systems allow for continuous measurement of the friction coefficient while the test wheel moves across the pavement surface at defined slip ratio. Moreover, devices operating with fixed slip between 12% and 20% are particularly well-suited for simulating real braking conditions of vehicles equipped with ABS (Anti-lock Braking Systems) [20]. Due to a wide variety of measurement devices, ongoing efforts are focused on identifying correlations between results obtained using different systems and on harmonizing measurement procedures.

3. RESEARCH PROGRAMME

3.1. Device

The British Pendulum Tester (BPT) is the most widely recognized device in the world for measuring pavement skid resistance properties. It simulates friction measurement with a fully locked wheel at a slip speed close to 10 km/h [18]. The test is conducted in accordance with international standards ASTM E303 [26] and EN 13036-4 [27]. The result is expressed as the Pendulum Test Value (PTV), which is the average of five tests and quantifies the energy loss as a rubber slider edge is drawn over a 126 mm test surface. Prior to testing, the surface must be cleaned and wetted. Stationary pendulum testing under real-world conditions is time-consuming due to the need to calibrate the device at each measurement point, which requires occupying a traffic lane.

The method for assessing skid resistance of road pavement using the ViaFriction device is based on evaluating road pavement resistance to slip in wet conditions by measuring longitudinal friction coefficient number (LFCN). Measurements are conducted using an electrically braked test wheel, which moves along the road surface at a controlled speed. The test wheel is aligned parallel to the direction of travel and perpendicular to the road surface [28]. Additionally, the ViaFriction system is equipped with a laser module for measuring macrotexture of the pavement. This module is mounted in front of the test wheel and enables measurement of mean profile depth (MPD) on dry pavement, within the same track where friction measurement is performed. This procedure complies with the requirements set out in EN ISO 13473-1 standard [24].

Fig. 4. British Pendulum Tester

Fig. 5. ViaFriction

In contrast to point sampling methods, which carry the risk of overlooking local areas with low skid resistance, the ViaFriction system enables continuous measurement of the friction coefficient. This allows for obtaining a detailed skid-resistance profile across the entire road network and effectively identifying sections with increased risk of skidding.

Tab. 1

Comparison of the British Pendulum Tester and ViaFriction

Feature	BPT	ViaFriction
Operational mode	stationary	continuous
Slip ratio	total (100%)	fixed (~17.8%)
Travel speed	0 km/h	60 km/h
Slip speed at the contact	~10 km/h	~10.7 km/h
Section length	local measurements	kilometers
Costs	low	high
Operation	manual	specialist
Standard	ASTM E303, PN-EN 13036-4	ASTM E2340
Application	pavement, passage, points	roads, road networks

3.2. Test Sections

At present, Poland lacks dedicated test tracks, which has necessitated conducting comparative measurements on roads with actual vehicular traffic. Measurement sections are located on national roads managed by the General Directorate of National Roads and Motorways, Opole Division. These sections have been selected to represent technological diversity. The most commonly used asphalt mixture for wearing courses of roads with medium to high traffic volumes is SMA (Stone Mastic Asphalt). Conversely, the asphalt mixture AC (Asphalt Concrete) is predominantly applied to pavements subject to lower traffic volumes.

Table 2 summarizes road sections selected for the study, including their locations, lengths of measurement segments, and a number of measurement points in case of tests conducted using the BPT. Table 3 presents pavement material characteristics of the tested road sections.

Tab. 2

List of road sections used for tests

No.	No. of road	Description of the section	Location on road [km+m]		No. of measure-ment points	Dis-tance [m]	Symbol
			beginning	end			
1	DK 94	Brzeg - Łosiów	146+800	147+900	12	1100	Brz–Los
2	DK 46k	Niemodlin Bypass, right side, slow lane	6+400	7+500	12	1100	Nie_byp
3	DK 46	Nysa - Pakosławice, right side, slow lane	56+850	57+650	9	800	Nys–Pak_sl
4	DK 46	Nysa - Pakosławice, left side, fast lane	57+650	56+850	9	800	Nys–Pak_fa
5	DK 46j	Myślina Bypass	1+400	2+300	10	900	Mys_byp
6	DK 39	Lubsza - Rogalice	61+000	62+000	11	1000	Lub–Rog

Tab. 3

Pavement characteristics of the tested road sections

Symbol	Technology			Traffic category
	pavement mix type	type of asphalt	type of aggregate	
Brz–Los	SMA 11	PMB 45/80-55	gabbro with graywacke/basalt	KR 5-6
Nie_byp	SMA 11	PMB 45/80-65	amphibolite, basalt, granite	KR 5-6
Nys–Pak_sl	SMA 11	PMB 45/80-65	gabbro	KR 5-6
Nys–Pak_fa	SMA 11	PMB 45/80-65	gabbro	KR 5-6
Mys_byp	SMA 8	PMB 45/80-55	gabbro	KR 5
Lub–Rog	AC 11	50/70	gabbro	KR 3-4

4. RESULTS

The conducted study aimed to determine the relationship between the measured values of PTV and MPD, and the friction coefficient obtained using the ViaFriction (VF) device. In order to assess the correlation between the obtained results, they were presented in pairs in graphical form and Pearson correlation coefficients (r) were determined for them. The strength of the relationship between the analysed variables was interpreted according to the following thresholds:

- $|r| \geq 0.9$ – very strong correlation,
- $0.9 > |r| \geq 0.7$ – strong correlation,
- $0.7 > |r| \geq 0.5$ – moderate correlation,
- $0.5 > |r| \geq 0.3$ – weak correlation,
- $|r| < 0.3$ – negligible correlation.

As mentioned earlier, all the tested road sections had pavements made of asphalt mixtures, but only four of them were of the same type, featuring stone mastic asphalt (SMA11) pavement. Therefore, the analysis of the results was conducted in two stages: first, correlations were assessed for all tested sections, and subsequently, correlation was evaluated exclusively for those surfaced with the SMA11 mixture. This approach aimed to assess the influence of pavement type on the observed dependencies.

4.1. Dependencies VF-PTV and VF-MPD

The data points shown in Fig. 6 and Fig. 7 are plotted using different markers depending on the road section they represent. The coordinates of these points correspond to: the x-axis – PTV values (Fig. 6) or MPD values (Fig. 7), and the y-axis – the friction coefficient values obtained using the VF device. Both figures also include a line representing linear approximation of the measurement results (solid line), described by an equation:

$$\mu_{\mathrm{VF}} = a \cdot n_{met} + b \tag{2}$$

where: μ_{VF} – the friction coefficient obtained from the VF device; n_{met} – the values of either PTV or MPD; a and b – the slope and intercept of the line, respectively. Approximation was performed using the least squares method, employing the Levenberg-Marquardt optimization algorithm implemented in MATLAB.

The dashed lines shown in the figures represent lines obtained by shifting linear approximation lines by the value of the standard deviation $\sigma(\mu_{\mathrm{VF}})$ and $2\sigma(\mu_{\mathrm{VF}})$, respectively. The ranges between these lines correspond to the areas within which ~68% and ~95% of the values of a normally distributed random variable $\mathcal{N}\big(\mu_{\mathrm{VF}}, \sigma(\mu_{\mathrm{VF}})\big)$ are expected to fall. The standard deviation of the residuals was determined according to the equation:

$$\sigma(\mu_{\mathrm{VF}}) = \sqrt{\frac{\sum_{i=1}^{n}\left(\mu_{\mathrm{VF},i} - (a \cdot n_{met,i} + b)\right)^2}{n-2}} \tag{3}$$

Additionally, the relative standard deviation of the residuals was calculated using the formula:

$$RSD_{\mathrm{res}}(\mu_{\mathrm{VF}}) = \frac{\sigma(\mu_{\mathrm{VF}})}{\bar{\mu}_{\mathrm{VF}}} \cdot 100\%, \tag{4}$$

where $\bar{\mu}_{\mathrm{VF}}$ is the mean value of the friction coefficient.

It should be noted that reporting only the correlation coefficient *r* may not be sufficient for an unequivocal assessment of the relationships' strength, as the compared values are subject to measurement errors. Therefore, the correlation coefficient should be analyzed together with its confidence interval. A summary of the Pearson coefficients, including the 95% confidence intervals for all analyzed relationships, is presented in Table 4.

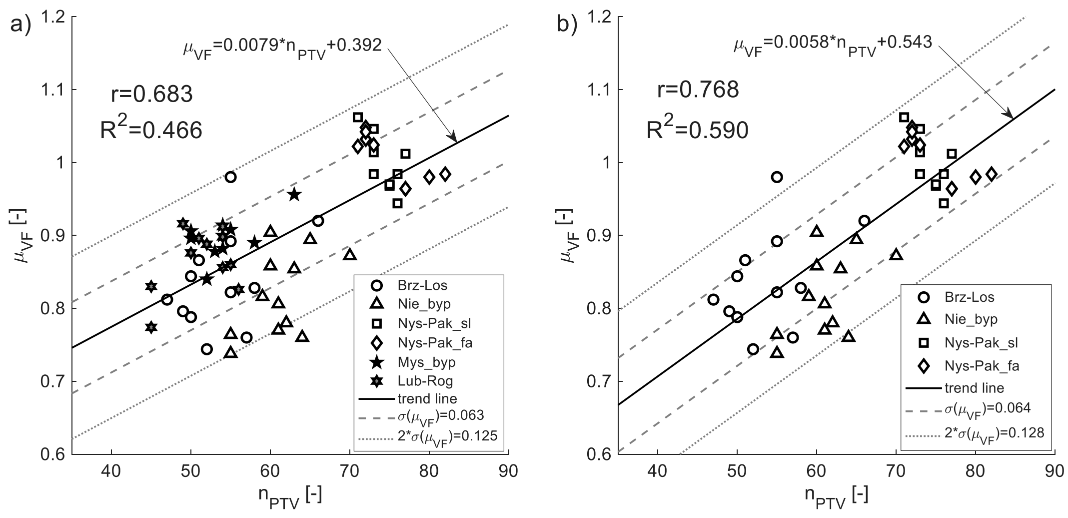

Fig. 6. Dependence between the BPT and VF results: a) all pavements, b) SMA11 only

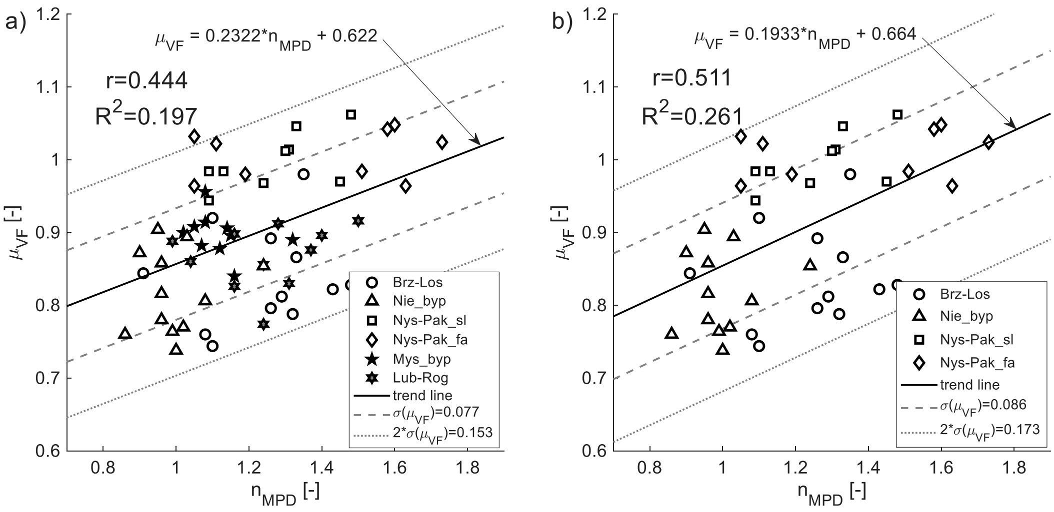

Fig. 7. Dependence between the MPD and VF results: a) all pavements, b) SMA11 only

Tab. 4

Pearson correlation coefficients R with 95% confidence intervals

Analyzed Pavement Types	Correlation Pair	95% CI Upper Limit	**Pearson's *r***	95% CI Lower Limit
ALL	PTV↔VF	0.796	**0.683**	0.523
	MPD↔VF	0.623	**0.444**	0.220
SMA11	PTV↔VF	0.853	**0.768**	0.642
	MPD↔VF	0.673	**0.511**	0.301

Comparing the Pearson correlation coefficients presented in Tab. 4, stronger correlations can be observed from the analyses conducted solely for SMA11 pavements ($r_{\text{PTV}} = 0.768, r_{\text{MPD}} = 0.511$) than for all the investigated road sections ($r_{\text{PTV}} = 0.683, r_{\text{MPD}} = 0.444$). However, the reduction in the correlations' strength is not substantial. Greater differences in Pearson coefficients are observed when comparing the VF-PTV and VF-MPD correlations: while the correlation between PTV and μ_{VF} values can be considered moderate to strong, the correlation between MPD and μ_{VF} is at best weak. This is also reflected in the relative standard deviation values, $RSD_{\text{res}}(\mu_{\text{VF}})$, which are ~7% for the $\mu_{\text{VF}}(\text{PTV})$ correlation and ~9% for the $\mu_{\text{VF}}(\text{MPD})$ correlation. Additionally, when considering the lower limit of the 95% confidence interval for the MPD-VF pairs, it can be observed that although the Pearson correlation coefficient *r* indicates a moderate (SMA11) or weak (ALL) correlation, the lower limit of the confidence interval for this data pair (equal to 0.301 and 0.220, respectively) falls within the range corresponding to the insignificant correlation. Whereas an analogous analysis performed for the PTV-VF pairs indicates a moderate level of correlation strength (with the lower limit of the confidence interval equal to 0.523 for ALL and 0.642 for SMA11).

The above conclusions confirm that it is not possible to unequivocally infer the friction coefficient values of a given pavement based solely on MPD measurement results. However, they can provide useful information if incorporated into the analysis of BPT test results.

4.2. Dependence between Friction Coefficient μ_{VF} and MPD and PTV values

To identify the relationship $\mu_{VF}(\mathrm{PTV}, \mathrm{MPD})$, linear regression analysis was employed in order to determine an expression for the friction coefficient in the following form:

$$\mu_{VF\_fit} = c \cdot n_{PTV} + d \cdot n_{MPD} + e \quad (5)$$

where the dependent variable μ_{VF_fit} represents the fitted value of the friction coefficient, and the independent variables n_{PTV} and n_{MPD} correspond to the values obtained from measurements using the BPT (PTV) and the profilometer (MPD), respectively. The coefficients *c*, *d*, and *e* denote the regression slopes and the intercept. The results of this analysis are presented in Fig. 8 as surfaces fitted to the measurement points for all analyzed pavements μ_{VF_ALL} and for the SMA11 pavement sections only μ_{VF_SMA11}.

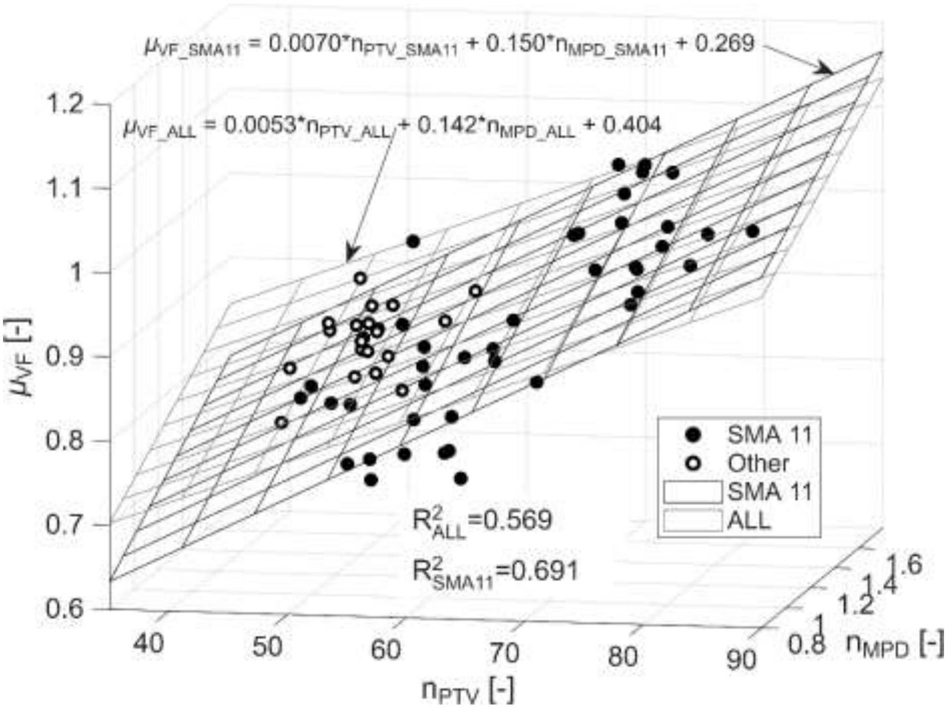

Fig. 8. Linear regression of the test results

In the case of multiple regression, the Pearson correlation coefficient cannot be used to assess the regression model. In such a case, the model fit is described using the coefficient of determination R^2, which, for simple linear regression with one explanatory variable (as in Section 4.1), is equal to the square of the Pearson correlation coefficient ($R^2 = r^2$). Hereinafter, it was assumed that the following values of the coefficient of determination indicate the degree of model fit to the data as follows:

- $|R^2| \geq 0.8$ – very good fit,
- $0.8 > |R^2| \geq 0.5$ – good fit,
- $0.5 > |R^2| \geq 0.25$ – moderate fit,
- $0.25 > |R^2| \geq 0.1$ – weak fit,
- $|R^2| < 0.1$ – no fit.

To facilitate the analysis of the results, they have been presented in the form of single-variable functions (Fig. 9), where the vertical axis μ_{VF} represents the friction coefficient values obtained from the VF measurements, and the horizontal axis $\mu_{\mathrm{VF\_fit}}$ corresponds to the values derived from linear regression. As in Fig. 6 and Fig. 7, the diagram also includes the best-fit regression line (solid line) and standard deviations of the approximation residuals (dashed lines). A summary of the coefficients of determination for the individual regression models, together with the relative standard deviations of the residuals, is presented in Tab. 5.

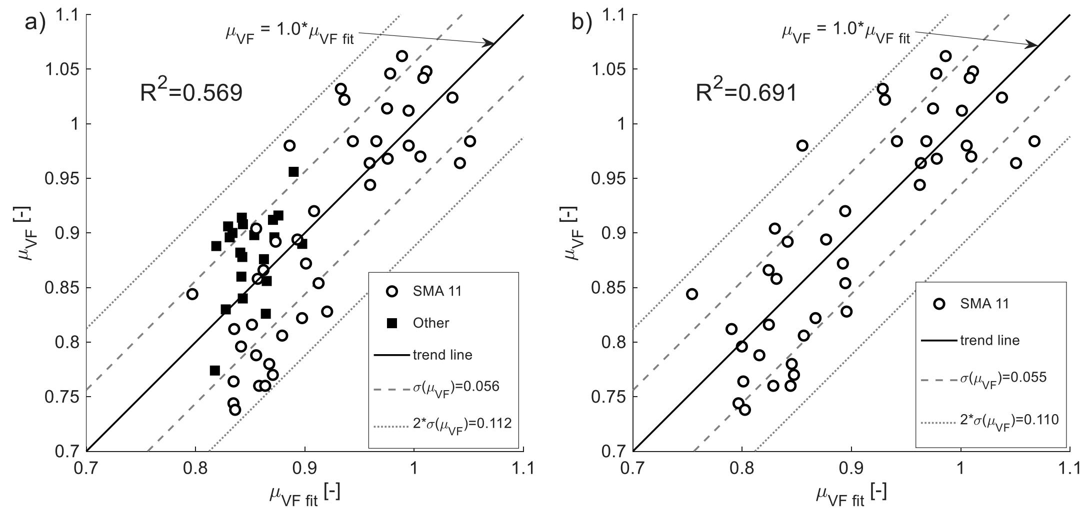

Fig. 9. Dependence between the results from VF and the linear regression:
a) all pavements, b) SMA11 only

Tab. 5
Coefficient of determination R^2 and relative standard deviation of residuals

Analyzed Pavement Types	Regression Model	Pearson's r	**Coefficient of determination R^2**	*RSD* of residuals
ALL	PTV↔VF	0.683	**0.466**	7.1%
	MPD↔VF	0.444	**0.197**	8.7%
	(PTV+MPD) ↔VF	–	**0.569**	6.4%
SMA11	PTV↔VF	0.768	**0.590**	7.3%
	MPD↔VF	0.511	**0.261**	9.8%
	(PTV+MPD) ↔VF	–	**0.691**	6.3%

The obtained coefficients of determination indicate an improvement in the model fit when multiple regression, $\mu_{\mathrm{VF}}(\mathrm{PTV},\mathrm{MPD})$, is applied, compared with models using a single explanatory variable, $\mu_{\mathrm{VF}}(\mathrm{PTV})$ and $\mu_{\mathrm{VF}}(\mathrm{MPD})$. In the case of simple linear regression models, their fit to the data is generally moderate or even weak. The only exception is the $\mu_{\mathrm{VF}}(\mathrm{PTV})$ model for SMA11, for which the fit may be considered good ($R^2 = 0{,}59$). For models including two explanatory variables, the fit is consistently good ($R^2_{\mathrm{ALL}} = 0.569, R^2_{\mathrm{SMA11}} =$

0.691), as also evidenced by the low values of the residual standard deviation, amounting to 6.4% and 6.3%, respectively.

The above analysis can be regarded as confirmation that the PTV and MPD parameters characterize the properties of the examined pavements at different scales (e.g., micro and macro) [15]. Considering both parameters simultaneously allows for a more comprehensive assessment of the influence of pavement texture on its friction coefficient [12,18].

5. CONCLUSIONS

The paper presents the results of studies on the friction coefficient of road pavements, μ_{VF} and PTV, measured respectively using continuous measurement device (ViaFriction) and point measurements (British Pendulum Tester), as well as the key parameter characterizing pavement texture — MPD [18], obtained using a laser profilometer. Six road sections, each approximately 1 km in length and surfaced with asphalt mixtures, were selected for the study, including four sections with the SMA11 (stone mastic asphalt) pavement, one with the SMA8 pavement, and one with AC11 (asphalt concrete) pavement. On the selected road sections, PBT measurements were taken at points spaced every 100 m. Subsequently, correlation analyses were conducted between the μ_{VF} and PTV datasets, and between the μ_{VF} and MPD datasets, performing the analysis twice: once for all selected road sections and once only for the SMA11 pavement sections.

The Pearson correlation coefficients obtained in this way indicate a strong correlation between the friction coefficients μ_{VF} and PTV for the SMA11 pavements ($r_{\mathrm{PTV}} = 0.768$) and a moderately strong correlation ($r_{\mathrm{PTV}} = 0.683$) between the measurement datasets for all analysed road sections. The obtained Pearson coefficients at this level contradict the conclusion presented in [3], which suggested that results obtained using ViaFriction and BPT exhibit low correlation and that different measurement methods show significant inconsistency. Reference [17] also reported a good correlation between test results obtained using the BPT and another continuous measurement device – the GripTester, operating at a constant slip of $s = 0.145$.

Higher Pearson correlation coefficients obtained from the analysis of data concerning only one pavement type (SMA11) confirm the absence of a universal relationship between pavement texture and friction forces – this relationship has an individual character depending on the pavement type [18]. The results also align with the assertion that the frictional properties of asphalt pavements are largely determined by the type and quality of the coarse aggregates used [5].

Subsequently, using multiple regression analysis, a relationship was found between the friction coefficient μ_{VF} and the values of PTV and MPD. The determination coefficients obtained from this approach indicate that including the MPD dataset in the analysis alongside the PTV values significantly improves the correlation between these data and the friction coefficients measured by VF ($R^2_{\mathrm{ALL}}(\mathrm{PTV}) = 0.466 \rightarrow R^2_{\mathrm{ALL}}(\mathrm{PTV, MPD}) = 0.569$; $R^2_{\mathrm{SMA11}}(\mathrm{PTV}) = 0.590 \rightarrow R^2_{\mathrm{SMA11}}(\mathrm{PTV, MPD}) = 0.691$), which is accompanied by a reduction in the relative standard deviation of the residuals by approximately 1% ($RSD_{\mathrm{ALL}}(\mathrm{PTV}) = 7.1\% \rightarrow RSD_{\mathrm{ALL}}(\mathrm{PTV, MPD}) = 6.4\%$; $RSD_{\mathrm{SMA11}}(\mathrm{PTV}) = 7.3\% \rightarrow RSD_{\mathrm{SMA11}}(\mathrm{PTV, MPD}) = 6.3\%$). Since MPD is a parameter describing the pavement's macrotexture, while PTV is mainly related to microtexture properties [18], it can be inferred that the friction coefficient of a road can be accurately predicted only by models incorporating variables describing pavement texture at both micro and macro scales. This conclusion is consistent with the findings of other researchers [12,18].

References

1. Kane Malal, Veronique Cerezo. 2015. „A contribution to tire/road friction modeling: From a sim-plified dynamic frictional contact model to a „Dynamic Friction Tester" model". *Wear* 342-343: 163-171. DOI: https://doi.org/10.1016/j.wear.2015.08.007.
2. Suhaimi Aminuddin, Abdul Rahman Baharuddin. 2019. „Threshold value of skid resistance and texture depth for Malaysia road". *IOP Conference Series: Materials Science and Engineering* 512: 012035. DOI: https://doi.org/10.1088/1757-899X/512/1/012035.
3. Wei Jincheng, Zhengchao Zhang, Yulin He, Qianwen Tan, Xiangpeng Yang, Dawei Wang, Markus Oeser. 2022. „Study on the skid resistance deterioration behavior of the SMA pavement". *Sustainability* 14: 2864. DOI: https://doi.org/10.3390/su14052864.
4. Wang Yan, Jingyu Hu, Fa'an Wang, Haoxuan Dong, Yongjun Yan, Yanjun Ren, Chaobin Zhou, Guodong Yin. 2022. „Tire road friction coefficient estimation: Review and research perspectives". *Chinese Journal of Mechanical Engineering* 35: 6. DOI: https://doi.org/10.1186/s10033-021-00675-z.
5. Kogbara Reginald, Eyad Masad, Emad Kassem, Tom Scarpas, Kumar Anupam. 2016. „A state-of-the-art review of parameters influencing measurement and modeling of skid resistance of asphalt pavements". *Construction and Building Materials* 114: 602-617. DOI: https://doi.org/10.1016/j.conbuildmat.2016.04.002.
6. Kageyama Ichiro, Yukiyo Kuriyagawa, Tetsunori Haraguchi, Tetsuya Kaneko, Minoru Nishio, Atsushi Watanabe. 2022. „Study on road friction database for traffic safety: Construction of a road friction-measuring device". *Inventions* 7(4): 90. DOI: https://doi.org/10.3390/inventions7040090.
7. Alamdarlo Mohsen, Saeid Hesami. 2020. „Measuring the effect of pavement porosity filling on skid resistance by numerical model and field test". *Measurement* 152: 107269. DOI: https://doi.org/10.1016/j.measurement.2019.107269.
8. Grigoriadis Kyriakos, Georgios Mavros, James Knowles, Antonios Pezouvanis. 2023. „Experimental investigation of tyre-road friction considering topographical roughness variation and flash temperature". *Tribology International* 181: 108294. DOI: https://doi.org/10.1016/j.triboint.2023.108294.
9. Persson Bo N.J. 2001. „Theory of rubber friction and contact mechanics". *The Journal of Chemical Physics* 115(8): 3840-3861. DOI: https://doi.org/10.1063/1.1388626.
10. Leontiev Dmytro, Smetanin German, Volodin Valerij, Malyi Viktor, Riabushenko Oleksandr, Tovt Bogdan. 2025. "Methods for Calculating Utilized Adhesion Between a Vehicle Tire and the Road Surface". *Vehicle and Electronics. Innovative Technologies* 28: 25-36. DOI: https://doi.org/10.30977/VEIT.2025.28.0.3.
11. Deng Qiangsheng, Zhan You, Liu Cheng, Qiu Yanjun, Zhang Allen. 2021. „Multiscale power spectrum analysis of 3D surface texture for prediction of asphalt pavement friction". *Construction and Building Materials* 293: 123506. DOI: https://doi.org/10.1016/j.conbuildmat.2021.123506.

12. Ergun Murat, Sukriye Iyinam, Faik Iyinam. 2005. „Prediction of road surface friction coefficient using only macro- and microtexture measurements". *Journal of transportation engineering* 131(4): 311-319. DOI: https://doi.org/10.1061/(ASCE)0733-947X(2005)131:4(311).
13. Kováč Matúš, Matej Brna, Martin Decký. 2021. „Pavement friction prediction using 3D texture parameters". *Coatings* 11(10): 1180. DOI: https://doi.org/10.3390/coatings11101180.
14. Giles C.G., B.E. Sabey, K.H.F. Cardew. 1965. „Development and performance of the portable skid resistance tester". *Rubber Chemistry and Technology* 38(4): 840-862. DOI: https://doi.org/10.5254/1.3535703.
15. Kotek Peter, Matúš Kováč. 2015. „Comparison of valuation of skid resistance of pavements by two device with standard methods". *Procedia Engineering* 111: 436-443. DOI: https://doi.org/10.1016/j.proeng.2015.07.113.
16. Jalalkamali Reza, Mohammad Mahdi Dibaee, Mohammad Hossain Jalal Kamali, Abolfazl Hassani. 2021. „An investigation of the relationship among skid resistance, mean texture depth and abrasion resistance for different macrotextures of concrete pavements". *Civil Engineering Infrastructures Journal* 54(2): 301-317. DOI: https://doi.org/10.22059/ceij.2020.297661.1656.
17. eScholarship. University of California Pavement Research Center. UC Davis Lu Qing, Steven Bruce. 2006. „Friction testing of pavement preservation treatments: Literature review". Available at: https://escholarship.org/uc/item/3jn462tc.
18. Zuniga-Garcia Natalia, Jorge A. Prozzi. 2019. „High-definition field texture measurements for predicting pavement friction". *Transportation Research Record* 2673(1): 246-260. DOI: https://doi.org/10.1177/0361198118821598.
19. Łądkiewicz-Krochmal Katarzyna. 2020. „Współczynnik tarcia nawierzchni – analiza zagadnień, urządzenia pomiarowe". *Drogownictwo* 2: 35-44. [In Polish: „Surface friction coefficient - analysis of issues, measurement devices". *Road Engineering*].
20. Hall J.W., K.L. Smith, L. Titus-Glover, J.C. Wambold, T.J. Yager, Z. Rado. 2009. „Guide for pavement friction". *Final Report for NCHRP Project 01-43*, Washington: The National Academies Press. DOI: https://doi.org/10.17226/23038.
21. Mohammad Diana Jumah, Mohammed Qadir Ismael. 2021. „Evaluating the friction characteristics of pavement surface for major arterial road". *Civil Engineering Journal* 7(12): 2011-2029. DOI: 10.28991/cej-2021-03091775.
22. Bukowski Leszek. 2017. „Zagadnienia dotyczące współczynnika tarcia na nawierzchni jezdni". *Drogownictwo* 10: 337-344. [In Polish: „Issues concerning the coefficient of friction on the road surface". *Road Engineering*].
23. Kouchaki Sareh, Hossein Roshani, Jorge A. Prozzi, Natalia Zuniga Garcia, Joaquin Bernardo Hernandez. 2018. „Field investigation of relationship between pavement surface texture and friction". *Transportation Research Record* 2672(8): 395-407. DOI: https://doi.org/10.1177/0361198118780955.
24. PN-EN ISO 13473-1:2019-04. Charakterystyka tekstury nawierzchni przy użyciu profili powierzchniowych – Część 1: Określanie średniej głębokości profilu. Warszawa: Polski Komitet Normalizacyjny. [In Polish: PN-EN ISO 13473-1:2019-04. *Characterization of pavement texture using surface profiles – Part 1: Determination of the mean profile depth*. Warsaw: Polish Committee of Standardization].

25. Wasilewska Marta, Władysław Gardziejczyk, Paweł Gierasimiuk, Marek Motylewicz. 2015. „Przegląd urządzeń do oceny właściwości przeciwpoślizgowych nawierzchni drogowych". In: *LVIII the Conference „Technical Road Days"*: 49-63. Association of Communication Engineers and Technicians of the RP, National Board, Warsaw, Poland. 18-20 November 2015, Białystok, Poland. ISBN: 978-83-7789-244-2. [In Polish: „Review of devices for assessing the anti-skid properties of road surfaces"].
26. ASTM E303-22:2022. *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. West Conshohocken, USA: ASTM International.
27. PN-EN 13036-4:2011. *Drogi samochodowe i lotniskowe – Metody badań – Część 4: Metoda pomiaru oporów poślizgu/poślizgnięcia na powierzchni: Próba wahadła*. Warszawa: Polski Komitet Normalizacyjny. [In Polish: PN-EN 13036-4:2011. *Roads and airports – Test methods – Part 4: Method of measuring the slip/skid resistance on the surface: Pendulum test*. Warsaw: Polish Committee of Standardization].
28. CEN/TS 15901-14:2016. *Road and airfield surface characteristics – Part 14: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCN): ViaFriction (Road Analyser and Recorder of ViaTech AS)*. Geneva: European Committee for Standardization.

Received 30.12.2025; accepted in revised form 19.05.2026